Experimental evidence for electric surface resistance in niobium

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Identifying the loss mechanisms of niobium cavities enables an accurate determination of applications for future accelerator projects and points to research topics required to mitigate current limitations. For several cavities an increasing surface resistance above a threshold field, saturating at higher field has been observed. Measurements on samples give evidence that this effect is caused by the surface electric field. The measured temperature and frequency dependence is consistent with a model that accounts for these losses by interface tunnel exchange between localized states in oxides formed along grain boundaries and the adjacent superconductor.

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Superconducting cavities made of niobium are nowadays routinely reaching surface resistances R_S as low as a few nΩ at surface magnetic fields above 100 mT corresponding to peak electric fields of over 50 MV/m, some performing close to the theoretical limit of the material[1]. Nevertheless many open questions concerning the field dependence of R_S exist. In the medium field region between a few and few tens of MV/m an increasing surface resistance is always observed. For some cavities this increase can be fitted with a polynomial of second order. These losses are described by models based on the surface magnetic field. Magnetic flux entry is thought to give rise to the quadratic term, which is dependent on temperature[2], while the linear term is correlated to hysteresis losses and independent of temperature[3].

For other cavities R_S is increasing above a threshold field and saturating at higher field. In this case the interface tunnel exchange model (ITE)[4] can be used to explain the data[5]. ITE assumes that electrons are exchanged between states in the superconductor and localized states in adjacent Nb_2O_5, preferably formed along grain boundaries. This exchange is caused by the surface electric field $\vec{E}$ penetrating only the dielectric oxide and not the superconductor, allowing for an exchange of electrons (i.e. a current) between the two materials within one RF period. Fig. 1 depicts the variation of the density of occupied electron states before and after an exposure of the surface to a stepwise increase or decrease of the electric field. The time after exposure is considered here long as compared to the relaxation time. Hence the occupation of states is in thermal equilibrium. However, for sufficiently shorter times as in the case of a time-varying RF field the electron current density $\vec{j}$ is not in quadrature with the electric field, which gives rise to RF losses $\vec{j}\cdot\vec{E}$, and hence to an electric surface resistance R_S^E. As the electrons relax and dissipate once per

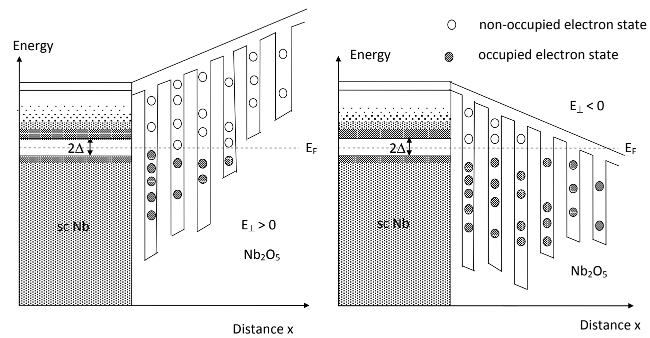

FIG. 1. Schematic view of energy states at thermal equilibrium near the interface of superconducting niobium and niobium-pentoxide Nb2O5; (left) after exposure to a positive and (right) to a negative electric field $E_\perp$. Note that the population of occupied electron states in Nb_2O_2 is modified after the exposure of the electric field which indicates current flow. The degree of half-toning indicates the density of states. E_F is the Fermi energy and Δ is the energy gap of superconducting niobium.

RF period R_S^E depends linearly on the RF frequency f. Within the superconducting energy gap 2Δ there are no electronic states available for a current to flow. Therefore there exists a threshold electric field E^0, depending on the thickness of the oxide x and on Δ, below which there is no current and hence no RF loss. In a quantitative analysis, Halbritter calculated the surface resistance for ITE losses as[4]:

$$R_\mathrm{S}^\mathrm{E} = R_\mathrm{S,sat}^\mathrm{E} f[\mathrm{GHz}]\left[\mathrm{e}^{-b/E} - \mathrm{e}^{-b/E^0}\right], \quad E \geq E^0, \quad (1)$$

where the parameters R_S^E (here normalized to 1 GHz) , b and E^0 are defined by

$$b = \frac{2\kappa\Delta\varepsilon_r}{\beta^* e}, \quad R_\mathrm{S,sat}^\mathrm{E} = \frac{2\pi\mu_0}{(2\kappa)^2 y}, \quad E^0 = \frac{\Delta\varepsilon_r}{ex\beta^*}$$

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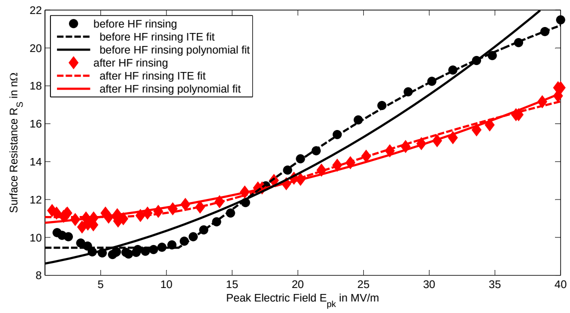

FIG. 2. Surface resistance of an elliptical 1300 MHz bulk niobium cavity at 2 K. Data taken by Romanenko et al.[6]

with

$$\kappa = \sqrt{2m\left(E_{\mathrm{c}} - E_{\mathrm{F}}\right)}/\hbar, \quad y^{-1} = \frac{\langle x n_{\mathrm{T}} \rangle \, e^2}{\varepsilon_0 \varepsilon_{\mathrm{r}}}.$$

The meaning of the physical parameters is the following: E_{c} and E_{F} are the energies of the conduction band and the Fermi energy, respectively; $\langle x n_{\mathrm{T}} \rangle$ is the averaged product of the density of trapped electron states n_{T} and the thickness of the oxide x; ε_{r} is the relative dielectric constant; β^* is the geometric field enhancement factor of the metal due to surface roughness; m, e, ε_0, μ_0 and $\hbar$ are the usual physical constants, such as the electron mass and electric charge, vacuum permittivity, vacuum permeability and Planck constant, in this order.

Figure 2 shows R_{S} as a function of the peak electric field E_{pk} at 2 K of a 1.3 GHz elliptical TESLA shaped[7] cavity. It was manufactured of fine grain bulk niobium (grain size of about 50 µm) and prepared by chemical polishing (BCP)[6]. Data was taken before and after hydrofluoric (HF) rinsing, which caused a removal of a surface layer of about 10 nm[6]. The dashed lines show fits to Eq. 1. It can be seen that the ITE model is very well applicable to the data before HF rinsing. Here a coefficient of determination R^2=0.996 is obtained for the fit parameter values of $R^{\mathrm{E}}_{\mathrm{S,sat}}$=22.3±1.5 nΩ, b=30±5 MV/m and E^0=10.9±0.8 MV/m. These phenomenological fit parameters correspond to physical meaningful parameters (compare with[8] and quotations therein) as β^*=1, ε_r=10, $E_{\mathrm{c}} - E_{\mathrm{F}}$=0.05 eV, Δ=1.3 meV, x=1.2 nm and $\langle n_{\mathrm{T}} \rangle$=7·10^{24} 1/(eVm^3). After HF rinsing the threshold disappears and a polynomial fit of second order yields a better representation of the data. ITE losses require localized states. Vanishing ITE after HF rinsing can be explained by the removal of the outer strongly oxidized layer.

A cavity test performed at fixed temperature and frequency is obviously not suited to test how the losses depend on these two external parameters. The Quadrupole Resonator[9] is a unique device enabling to test R_{S} of superconducting samples over a wide parameter range. It features two excitable modes at 400 and 800 MHz with identical magnetic field configuration on the sample surface. The ratio between electric and magnetic field for these two modes is proportional to f. For example for a peak magnetic field B_{p}=10 mT, the peak electric fields are E_{p} =0.52 and 1.04 MV/m for 400 and 800 MHz, respectively[10]. This feature allows for a separation of magnetic and electrical losses from measurement data by comparison with theoretical models.

To test the properties of ITE a sample is required for which these temperature independent losses remain dominant up to relatively large temperatures. Therefore a strongly oxidized (10 years under normal air) niobium thin film sample sputtered on a copper substrate was tested with the Quadrupole Resonator. It has a grain size of a few nm[5], several orders of magnitude smaller than typical values of fine grain bulk niobium surfaces prepared for accelerating cavities. The sample was measured at 400 and 800 MHz over a temperature range between 2 and 4.5 K. Figure 3 shows R_{S} vs. the peak magnetic field B_{pk} on the sample. Only about one fifth of the data is plotted. To calculate R_{S}, the measured dissipated RF power on the sample surface P_{RF}, is assumed as solely caused by the surface magnetic field using

$$R_{\mathrm{S}} = \frac{2\mu_0^2 P_{\mathrm{RF}}}{\int\limits_{\mathrm{Sample}} |\vec{B}|^2 \mathrm{d}S}. \tag{2}$$

Curves for a different temperature and the same frequency are parallel. Therefore the field dependent part of R_{S} can be assumed as independent of temperature. Between 0 and 35 mT R_{S} increases by about 60 nΩ at 400 MHz and by about 600 nΩ at 800 MHz. These two features cannot be explained by any model predicting a linear or quadratic increase of the surface resistance with magnetic field, such as[2,3,11]. In the following it is assumed that the field dependent contribution of R_{S} is caused by the surface electric field to test whether the data is consistent with the ITE model. First, the field independent residual and BCS losses are subtracted from each curve individually. Then R_{S} is derived assuming all other losses to be caused by the surface electric field using

$$R^{\mathrm{E}}_{\mathrm{S}} = \frac{2\mu_0 P_{\mathrm{RF}}}{\varepsilon_0 \int\limits_{\mathrm{Sample}} |\vec{E}|^2 \mathrm{d}S}. \tag{3}$$

From Fig. 4 the linear scaling of $R^{\mathrm{E}}_{\mathrm{S}}$ with frequency as predicted by the ITE model becomes apparent. It furthermore becomes more evident that these field dependent losses are independent on temperature. Note that due to the field configuration of the Quadrupole Resonator the ratio

$$\int\limits_{\mathrm{Sample}} |\vec{E}|^2 \mathrm{d}S \Big/ \int\limits_{\mathrm{Sample}} |\vec{B}|^2 \mathrm{d}S \propto f^2. \tag{4}$$

At low field some $R^{\mathrm{E}}_{\mathrm{S}}$ values for 400 MHz are negative. At 400 MHz an electric surface resistance of 1000 nΩ corresponds to a magnetic surface resistance of only 18.7 nΩ. Comparison with Fig. 3 shows that the majority of the

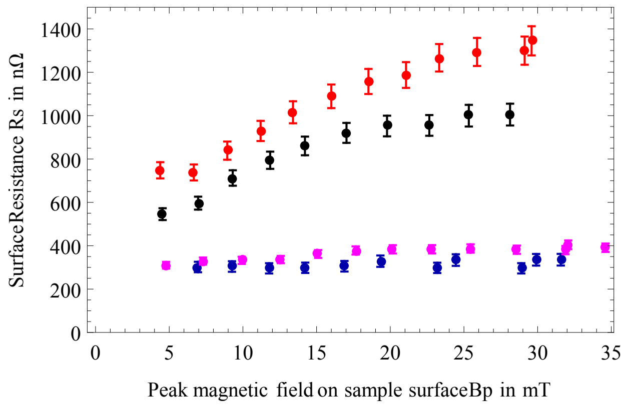

FIG. 3. Surface resistance R_S of a niobium film sample tested with Quadrupole Resonator at 400 MHz (2.5 K (blue), 4 K (magenta)) and 800 MHz (2.5 K (black), 4 K (red). R_S was obtained under the assumption that all losses are solely caused by the surface magnetic field.

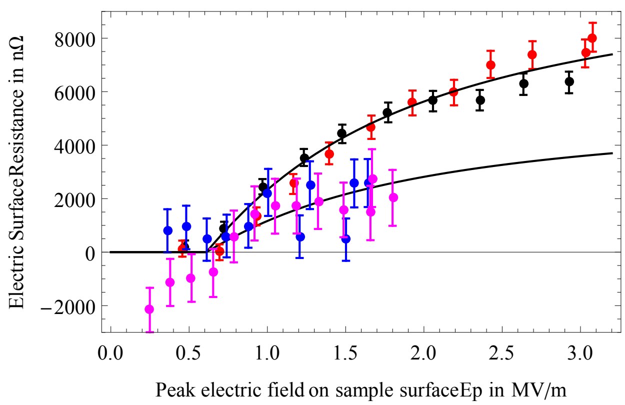

FIG. 4. Electric surface resistance at 400 MHz (2.5 K (blue), 4 K (magenta)) and 800 MHz (2.5 K (black), 4 K (red)) of a niobium film sample. The lines show predictions from a collective least squares multiparameter fit to a data set comprising 183 values $R_S(f, T, E)$. The data dsiplayed is the same as in Fig. 3 without losses independent on field strength. These were subtracted from each curve. All field dependent losses are assumed to be caused by the surface electric field.

overall losses at 400 MHz are caused by the surface magnetic field (BCS and residual losses). The complete data set consisting of 183 values $R_S(f, T, E)$ has been collectively fitted to Eq. (1). A χ^2=167.9 was obtained for the fit parameter values of $R^{E}_{S,sat}$=17000±500 nΩ, b=1.06±0.10 MV/m and E^0=0.610±0.015 MV/m. The fact that χ^2 is close to the number of data points indicates that the measurement is well represented by the model. For this sample $R^{E}_{S,Sat}$ is three orders of magnitude larger than for the bulk niobium cavity. This can be correlated to the smaller grain size and stronger oxidation of the sample. The onset field E^0 is one order of magnitude smaller for the sample, indicating the presence of a thicker oxidized layer and/or stronger field enhancement at grain boundaries. Also here, the phenomenological fit parameters $R^{E}_{S,sat}$, b and E^0 can be correlated to a set of physical parameters with meaningful values as β^*=10, ε_r=10, $E_c - E_F$=0.01 eV, Δ=1.04 meV, x=1.7 nm and $\langle n_T \rangle$=7·10^{26} 1/(eVm^3). A critical assessment of these numbers lies however beyond the scope of this paper.

In conclusion, the dependency of the surface resistance on the applied field strength is different for different cavities and/or surface preparations. This indicates a variety of different dominant field dependent loss mechanisms. Some cavities exhibit an R_S increasing above a threshold field saturating at higher field. In this paper it has been shown that measurements on a state of the art bulk niobium cavity, showing this behavior of R_S on the surface electric field, can be well described by the ITE model. To further test the predictions of the ITE model a strongly oxidized niobium thin film sample with smaller grain size was tested with the Quadrupole Resonator. These measurements showed field dependent losses independent on temperature, which scale linearly with frequency, if one assumes that they are caused by the surface electric field. These findings are consistent with the predictions of the ITE model. They allow to better understand the field dependent surface resistance of superconducting niobium. This can be used for the development of future accelerating cavities. In particular a possible explanation for the larger field dependent surface resistance found in some cavities produced of niobium films on copper substrates is given by the ITE model.

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